James Watt and his Linkages

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Keywords

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James Watt's name is synonymous with steam engines but there is another equally impressive facet to his technical accomplishments in the areas of design and manufacture of machines. In this article, we highlight his contributions to the design of linkages, which are assemblies of rigid bodies that perform intricate mechanical motions. The linkages described here range from the ones that can draw a straight line to those that can replicate three-dimensional objects through purely mechanical movements.

We use a compass to draw a circle and a scale (a *ruler* as it is sometimes called) for a straight line. We *generate* a circle with the help of a compass whereas we *copy* a straight line from a scale. If the scale is not straight, so will be the line we copy. It is difficult and expensive to make a perfectly straight scale. It was more so before the industrial revolution when manufacturing techniques were not as good as they are today. Hence, craftsmen of that time explored alternate means for *generating* a straight line. A particularly vexing problem encountered by craftsmen of the mid 18th century was guiding a piston inside a cylinder of a steam engine. The first person to come up with a solution, although approximate but good enough for practical purposes, was James Watt.

The approximate straight-line linkage that James Watt developed is known today as the Watt's linkage. This and other inventions of Watt defined a field called *linkage synthesis* and occupied the minds of many engineers, scientists, and mathematicians since then. Thus, James Watt was not just an inventor who played a key role in ushering in the industrial revolution but was also the one who played a key role in transforming the image of able craftsmen into engineers and scientists. By discussing his contributions to linkages, we present a profile of Watt that is much more than the person who improved Newcomen's steam engine and made steam power generation portable.

Watt's Straight-line Linkage

Let us turn to the question of why Watt required a straight-line linkage or other linkages that he invented. *Figures* 1a,b show a linkage (see *Box* 1 to know what linkages are) in the steam engine that was invented by Thomas Newcomen in 1712 – almost 24 years before James Watt was born. This linkage, which is simply a lever driven by steam power, was used to pump water out of mines. It had a wooden beam pinned to a base with sectors attached at its either end. Iron chains tangentially hung from the sectors and held a pump-rod and a piston-rod. Since a chain hanging from one point remains vertical due to gravity, the rods could be guided vertically. But a chain will be straight only when it is pulled. We cannot push through with a chain. In a double-acting steam engine that Watt invented, there was a need to push and pull on the piston-rod. Manufacturing a snugly fitting and yet freely movable piston-cylinder assembly is one option. But it was not practicable at that time. Watt did have access to an able ironmaster, John Wilkinson, who could bore the best cylindrical hole at that time for as large a diameter as 50 in. But it was expensive and Watt wanted a better solution than this. So, he set out to find a linkage that would give straight-line motion. It is important that such a linkage should only have pin joints and no sliding joints because a sliding joint again takes one back to the problem of not being able to machine a perfectly straight slider.

Watt's solution to this problem was as remarkable as his other significant contributions to steam engines such as a separate condenser and double-acting cylinder were. His creative thought took

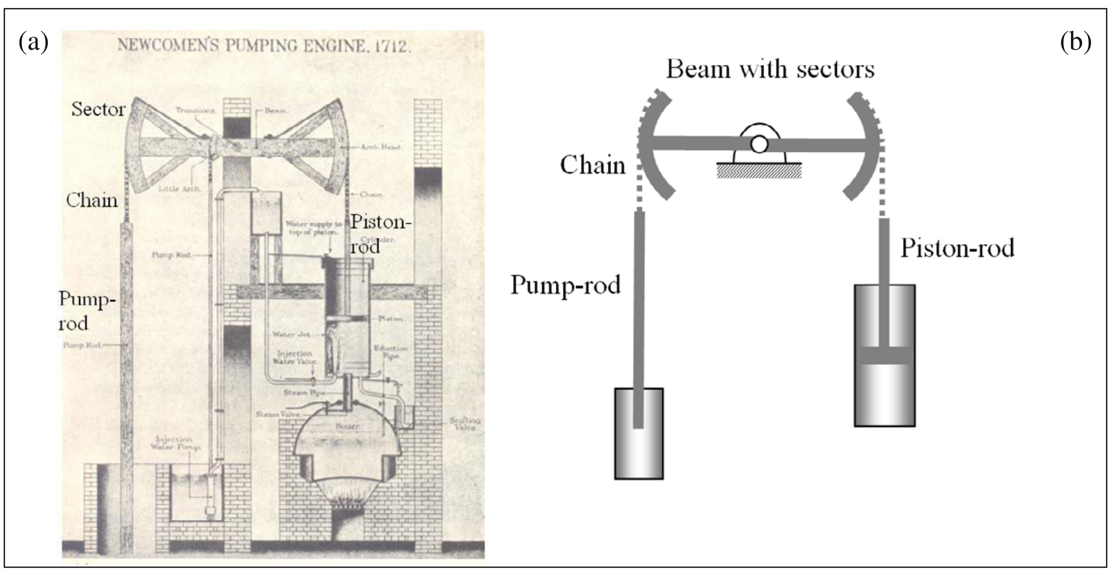

Figure 1. (a) Newcomen water-pumping steam engine [1]; (b) a sketch of the simple linkage involved in it.

Box 1. Linkages

A linkage is an assembly of rigid bodies. A rigid body does not change its shape upon application of forces. A solid metal rod can be considered to be a rigid body even though nothing is perfectly rigid. If we want to rotate it about a point, we use a pin joint and connect it to a base. Now, we take another rigid rod and connect it to the other end of the first rod. We then take a third one and connect it to the free end of the second rod. To complete the assembly, we connect the free end of the third rod to the base. All connections are with pin joints. What we now have is an assembly of four bodies (three rods and the base). See *Figure* A(i). Such an assembly is a *linkage*. In particular, it is a *four-bar linkage*. A linkage can consist of any number of bodies and connections as well as a variety of connection, besides pin joints. Other types of connections include: a sliding joint, a ball-and-socket joint, a gear-pair, a cam-and-follower, chains-sprocket, belt-pulley, etc. *Figure* A(ii) shows the familiar slider-crank linkage with a sliding joint and three pin joints.

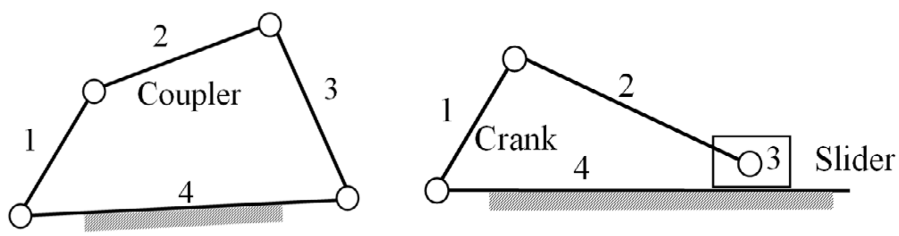

Figure* A. (i) *A four-bar linkage. **(ii) *A slider-crank linkage.***

him in a direction that nobody had thought of before. Although linkages were known, everyone until then had focused attention on the ends of the rigid bodies where joints are located. Watt examined the motion of an interior point of the middle body called the *coupler* (marked 2 in *Figure* A(i)). We present the details of his approximate straight-line linkage next.

Watt's straight-line linkage is shown in *Figure* 2. It consists of three movable rigid bodies labeled DE, EB and BC connected with pin joints at D, E, B and C. The pin joints at D and C connect the bodies to a fixed base-frame while the joints at E and B can freely move about in a plane. Point F is the midpoint of BE. The lengths of DE and BC are equal. As BC is rotated about C, point F traces an approximate vertical straight line in a small segment of its locus.

Note that point F, being the midpoint of EB will traverse a vertical line if the horizontal motions of points B and C are equal and opposite. It is quite evident from *Figure* 2 that when B moves to the right, E moves to the left. For a short range of motion of this linkage, the horizontal movements of B and E are almost equal in magnitude. Thus, an approximate straight-line linkage is obtained.

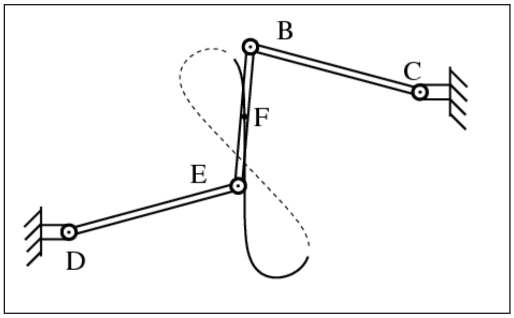

Figure 2. Watt's approximate straight-line linkage. The curve shown is the locus of point F. It has a short vertical segment that approximates a straight line.

Figure 2 also shows the locus of the midpoint of BE. It is called a *coupler curve* because EB, the middle body of a four-bar linkage, is called a *coupler*. The coupler curve of Watt's linkage is shown in *Figure* 2. Half of the coupler curve is shown as a solid line and the other half in dashes. This is because a transition occurs in the linkage at the points where dashed and solid lines meet. To understand this, we need to know more about the nature of this curve. This curve has many interesting properties and is one of the most fascinating planar curves. The variety of shapes this curve can assume is available in an atlas created by Hrones and Nelson, which is in use even today by linkage designers. Watt was the first one to have thought of using this curve. One of the properties of this curve is that it cannot have a perfectly straight segment. More bodies are necessary to get an exact straight-line motion. Perhaps Watt did not know this property but he was able to get a novel solution to the problem he was facing. Watt's approximate straight-line linkage aroused interest in many great mathematicians and geometers such as Chebyshev and Sylvester (see *Figure* 3 for developments on straight-line linkages using only pin points). It led to the fascinating field of kinematic analysis and synthesis of linkages.

Kinematics, a term coined by André-Marie Ampere (*cinematique* derived from Greek roots *kinema* meaning motion or *kinein* meaning to move), is an area of study where motion is analyzed without regard to the forces that cause it. It is essentially geometry in motion. Understanding the changing geometry of a linkage needs kinematic analysis. Kinematic synthesis or linkage synthesis entails conceiving an arrangement of assembled bodies and determining their sizes to get the desired motion. That is exactly what Watt did to generate a straight line using only pin joints. Thus, Watt is deservedly credited with the initiation of an orderly study of kinematic synthesis of linkages.

From Watt's correspondence, it is evident that Watt himself had realized the importance of his invention of the straight-line linkage. Apparently, he thought that this was one of his most significant accomplishments: he wrote to his son several years after this invention, "*though I am not over anxious after fame, yet I am more proud of the parallel motion than of any other mechanical invention I have ever made*." Watt's linkage was known as the *parallel motion linkage* during his time but not now. Immediately after conceiving this idea in 1784, he had written to his friend and business partner Matthew Boulton: "*I have got a glimpse of a method*

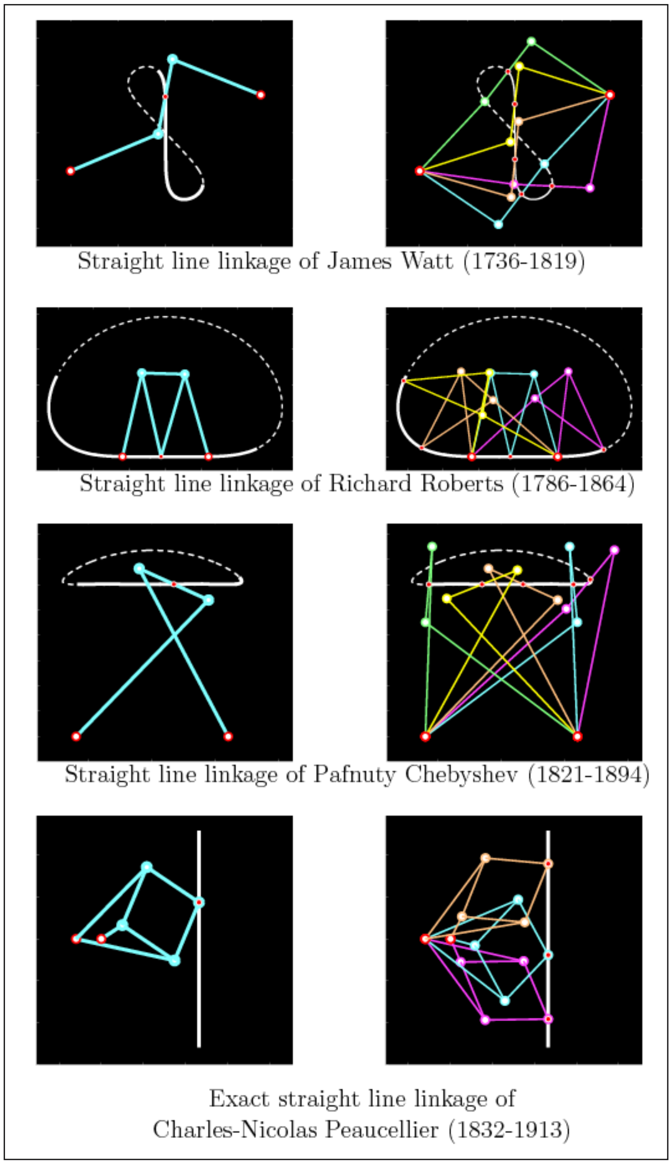

Figure 3. Watt's straight-line linkage and the others that it inspired. The pictures in the left column show the linkages in one position and the right in many positions.

of causing the piston-rod to move up and down perpendicularly…I think it a very probable thing to succeed, and one of the most ingenious simple pieces of mechanisms I have contrived". Watt did successfully use this linkage in his subsequent engines.

Watt's mechanical inventiveness and practical bent of mind were clear from the way he combined this linkage with a *pantograph* to achieve compactness in the engine. A pantograph is a linkage consisting of a parallelogram that helps in duplicating the scaled motion of one of its points to another of its points. This idea of Watt is highly appreciated by kinematicians and we describe it briefly here.

Figure 4 shows Watt's double-acting steam engine where Watt's straight-line linkage was used. At the top, one can notice a beam pinned at its midpoint. This beam was called a *great beam* and existed in Newcomen's engine. As the piston reciprocates due to the steam action, the great beam oscillates about its pin joint. This oscillatory motion is transmitted to a rotating wheel at the right through a rod. Let us understand how Watt's straight-line linkage was combined with a pantograph linkage in this engine.

Figure 5a shows a sketch with the great beam pivoted at C and Watt's straight-line linkage consisting of bodies DE, EB and BC. Body BC is extended up to H and thus BH is the great

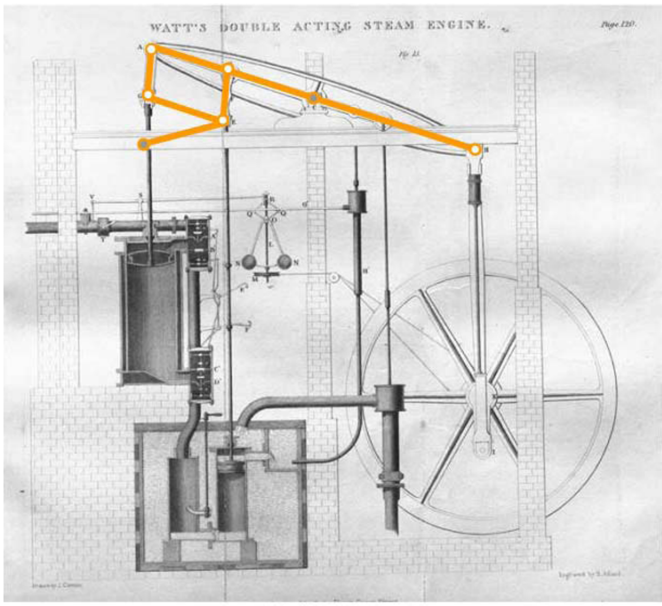

Figure 4. Watt's double-acting steam engine that incorporated his straight-line linkage along with a pantograph [2]. The schematic of the linkage is overlaid for clarity. The two fixed pin joints are filled with gray colour while the other five are shown in white.

beam. The cap symbol at the pin joint C indicates that BC and CH are part of the same rigid body. The piston is to be connected to point F through a rod. As the piston reciprocates vertically, so does point F. This straight-line motion of F is converted to oscillating rotary motion of BC by the Watt's linkage. While this linkage serves the purpose, the design is not compact since D is located at quite a distance away from the central portion. One can scale down the Watt's linkage, say by half, as shown in *Figure* 5b but it would reduce the motion of F thus restricting the stroke length of the piston.

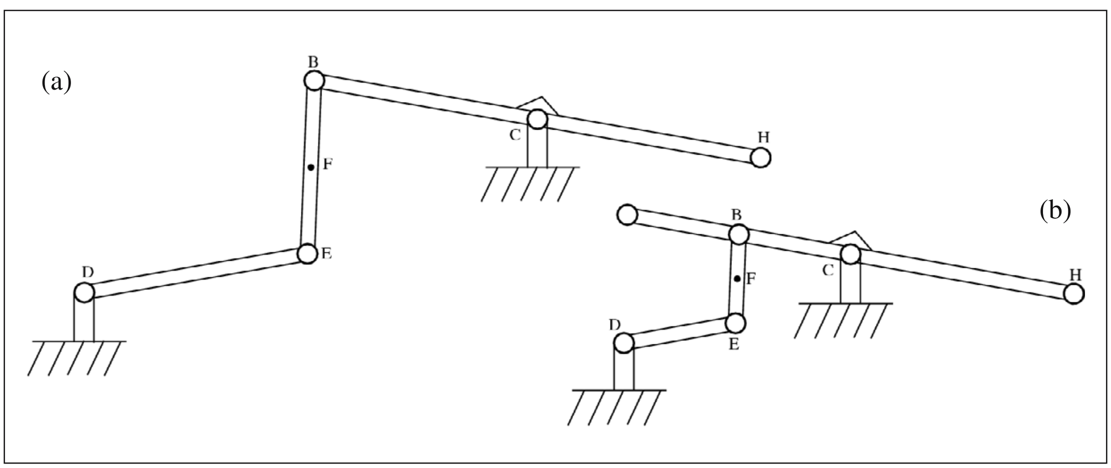

Figure 5. (a) Watt's linkage with one body acting as the great beam. (b) An attempt to reduce the size, which reduces the stroke length of the piston.

In order to overcome the reduced stroke length, Watt made use of a pantograph linkage (see *Figure* 6) . Links AC and BD are such that BD/AC = OB/OA. If FE were to be absent, points D and C would trace arbitrary paths on the plane unlike A and B which can only trace arcs of a circle. If we somehow ensure that D, C and O remain collinear and OC/OD is a constant, then the path traced by D is a scaled version of the path traced by C. The scaling is about O by a factor of OD/OC. In order to achieve collinearity and constant ratio, we only need to ensure that AC and BD remain parallel. This follows from a theorem of geometry concerning similar triangles. This parallelism is achieved by introducing FE so that FEBA is a parallelogram.

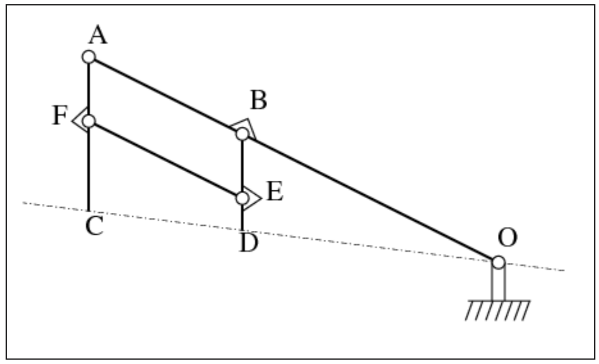

Figure 6. A pantograph linkage.

Figure 7 shows the pantograph linkage combined with Watt's straight-line linkage. The motion of point F (of *Figure* 5b) is scaled back at point G through the pantograph shown in the figure. Thus, Watt was able to put his clever invention to practical use through an elegant (certainly not simple for his times) modification. This trait was visible in many other inventions of Watt where he was able to cleverly adapt and improve upon existing knowledge.

A graph representation of this linkage in terms of the number of bodies and joints is known as Watt's six-bar chain (see *Figure* 8a). There is another eponymous six-bar chain (*Figure* 8b) credited to Robert Stephenson, son of George Stephenson – the father of railways. Watt's and Stephenson's six-bar chains are the only possible assemblies of six bodies that have completely determined motion with only a single actuator. We next examine a few other linkages that Watt developed.

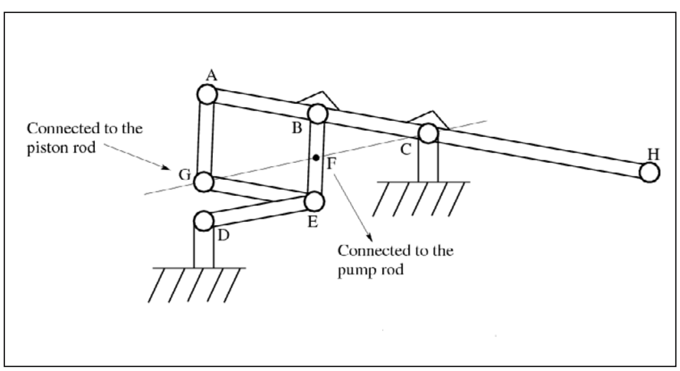

Figure 7. Watt's solution to the straight-line guidance problem. The sketch shows how the straight-line linkage and pantograph were combined without reducing the stroke and by avoiding an over-sized linkage.

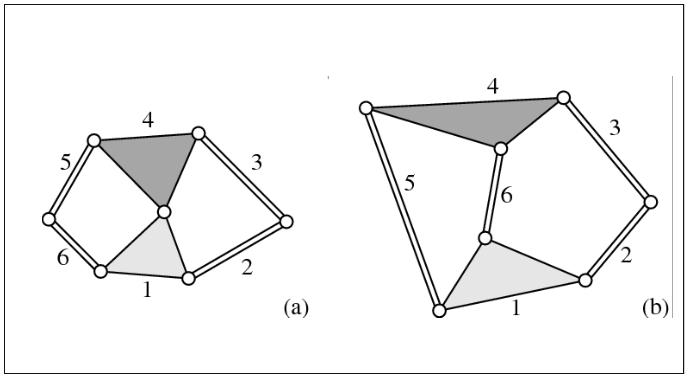

Figure 8. (a) A graph of Watt's six-bar chain; referring to Figure 7, body 1 is ABCH, body 2 is AG, body 3 is GE, body 4 is BE, body 5 is ED, and body 6 is the fixed frame DC, (b) a graph of Stephenson's six-bar chain; a linkage based on this was used in a valve mechanism in a steam locomotive. The historic ship Titanic had this valve in its engine.

Rotary Engine Linkages

Newcomen's engine and Watt's early engines moved the piston back and forth along a straight line using steam power. This reciprocating motion is useful for some applications but not all. Continuous rotary motion of a wheel was necessary to drive many machines of that time just as it is now. Conversion of linear reciprocating motion to rotary motion, although trivial today, was not obvious or practical in those times. A practical solution of that time was to pump the water up into a reservoir and let it fall on a water-wheel. But this was cumbersome. So, Watt and other engineers worked on other means to convert linear motion to rotary motion.

Slider-crank linkages (see *Figure* A (ii) of *Box* 1) were known to Leonardo da Vinci in the 15th century. Perhaps they existed much before that. But several accomplished engineers of the steam engine era believed that a simple piston-crank linkage would not serve well because of the irregularity of generated power or because of the fear that a crank will not be able to bear the loads. This opinion was shared by John Smeaton, who had contributed a lot to the development of steam engines and is the father of the civil engineering profession, for whom Watt had a lot of admiration. Perhaps because of that or due to fear of infringement of a patent by his contemporaries, Watt too did not stick to a slider-crank linkage although he had experimented with it. Historical reports say that James Pickard, who had employed Mathew Wasborough to build an engine for his flour mill, had a patent that involved a crank. So, Watt explicitly avoided a crank and attempted new designs. One of them was the sun-planet gear linkage, which is a somewhat roundabout solution when we think about it today.

Figure 9a shows the photograph of the sun-planet or epicyclic gear linkage. *Figure* 9b shows the schematic of the linkage. It has two gears that mesh with each other. One gear is fixed to a base-frame with a pin joint and turns with the shaft from which power can be tapped for any application. This gear is the sun gear because the second gear – called the planet gear – revolves around the sun gear. The planet gear is rigidly connected using two pin joints to a connecting rod

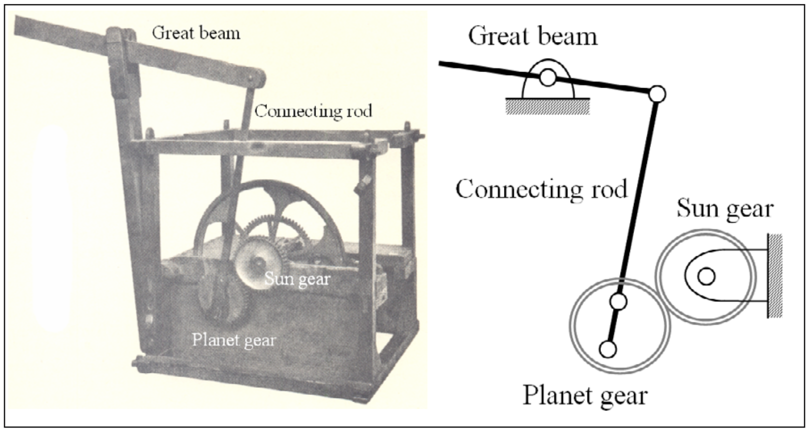

Figure 9. Watt's sun-planet gear linkage for converting reciprocating linear motion into continuous rotary motion. (a) Photograph [1]. (b) Schematic.

which in turn is attached to the great beam. The planet in this linkage does not spin about its centre. By making the radii of the planet and gear the same, Watt made it possible to rotate the sun gear twice for every cycle of the steam engine. This made the required size of the flywheel small because it rotates twice as fast as otherwise. A flywheel was added to smooth out the periodic bursts of forces coming from a steam engine.

Today, the invention of the sun-planet gear linkage is sometimes credited to Watt's loyal employee and an inventive engineer, William Murdoch. But in a letter written by Watt to Boulton on January 3rd, 1782, Watt says: "*…I have tried a model of one of my old plans of rotative engines revived and executed by W.M(urdock) and which merits being included as a fifth method…*". Here, Watt was alluding to the methods of converting linear reciprocating motion into continuous rotary motion. The other four were: (i) a two-cylinder engine with cranks that were out of phase with counterweights on the shaft to overcome the difficulties of a dead-centre position when a sliding piston cannot transmit power to the rotating shaft; (ii) a modification of a rack arrangement; (iii) the internally-geared connecting rod; and (iv) the swash plate and crown-cam motion. It is believed that the fifth method of sun-planet gear method was added in the 1782 patent upon a suggestion of Murdock. It was one of the simplest and most practicable of all the five methods described in the patent specifications.

Centrifugal Governor

A third important linkage that is attributed to James Watt is the *Watt's governor*. Watt neither invented it nor patented its use but many believe that he used a centrifugal governor in a steam engine for the first time. A centrifugal governor, shown in *Figure* 10a with a schematic in *Figure* 10b, is a marvelous example of automatic control. It was used in mills to regulate the distance

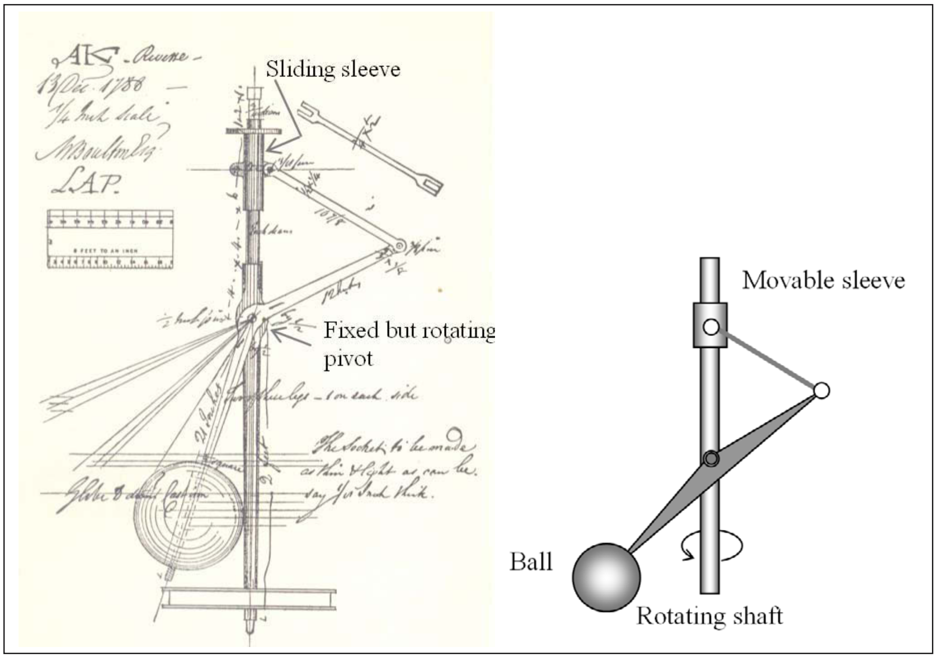

Figure 10. Watt's centrifugal governor. (a) Photograph [1]. (b) Schematic.

and pressure between the mill-stone and bed-stone as per the speed of the engine. Boulton saw it in a mill and was amazed at the way it worked and wrote to Watt about it in a small paragraph in a letter in 1788. That was all Watt needed to come up with the design shown in *Figure* 10a just five months later. Watt cleverly used it to control the throttle valve that lets the steam in. The governor works as follows.

It is essentially a slider-crank linkage (see *Figure* A(ii) of *Box* 1) but it is driven by the centrifugal force that a rotating body would experience. Here, a heavy ball is hung like a pendulum from the pivot of the crank in the slider-crank linkage wherein the pivot itself can spin around the axis of a vertical shaft but is fixed to the shaft. The pendulum rod is extended beyond the pivot to serve as the crank in the slider-crank. The sliding pivot – a sleeve – also can spin around and hence can slide. As the shaft starts rotating, the ball moves away from the centre of the shaft due to the centrifugal force. This makes the sleeve move down closer to the fixed pivot. This movement is used to open or close the throttle valve. A prior adjustment sets the required opening of the valve corresponding to a speed of rotation. Thus, the rotation speed of the engine shaft is used to regulate the steam that is let in. In general, another ball and the linkage are used for symmetry and balance.

The centrifugal governor is yet another example of how Watt could invent and adapt anything and everything that made the steam engine better.

Pressure-indicating Linkage

Before discussing this linkage, we shall slightly digress to mention how *watt* (W) came to be the unit for power rating in modern times. Measuring the capacity of an engine in terms of horses was not new in Watt's time. It was only natural to do that because horses used to do the work before steam engines came along. Watt went further and estimated the power a horse contributes. He observed that a mill-horse walks in a circular path of 24 ft diameter 2.4 times in a minute. He measured that a horse exerts a pull of 180 lb. So, the work done by a horse per minute is $\pi \times 24 \times 2.4 \times 180 = 32572$ ft.lb/min. It appears that Watt, for convenience, rounded it off to 33,000 ft.lb/min or 550 ft.lb/s, which is used even today as the old unit of power, the *horse power* or HP to rate engines. One HP is equal to 746 W. The watt unit for power was adopted by the Second Congress of the British Association for the Advancement of Science in 1889, and by the General Conference on the Weights and Measures in 1960 as the unit of power incorporated in the International System of Units (SI). It is a well-deserved tribute to James Watt.

It is easy to imagine how James Watt would have measured the number of turns a horse would make in a minute on a circular track of 24 ft diameter. But how did he estimate the force exerted by a horse? All horses would not exert the same force and a given horse would not always exert the same force. So, perhaps he compared the power of a steam engine that pumped water with that of a horse-driven pump. In order to rate the power of a steam engine he invented a pressure gauge to measure the variations of the pressure in the engine's cylinder. James Watt called his pressure gauge an *indicator*. Watt's indicator is shown in *Figure* 11a with its schematic in *Figure* 11b. It is a simple linkage but uses a helical spring. Its linkage structure is akin to that of the Newcomen engine but the novelty lies in the way Watt used it. An instrument of this kind needs calibration with known pressure. Watt knew this very well as he had devised a method to determine the power of pumping engines.

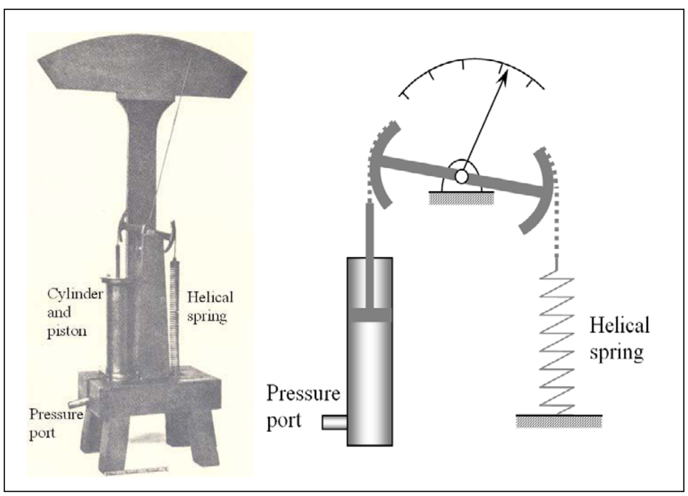

Figure 11. Watt's pressure indicator. (a) Photograph [1]. (b) Schematic.

Perspective-drawing Linkage

Around the time Watt conceived his remarkable idea of a separate condenser for a steam engine to improve its efficiency, he also invented a perspective-drawing link-

age in 1765. It is shown in *Figure* 12. A part of this linkage is similar to that of a mini-drafter used for engineering drawing. This part consists of two parallelograms in series, with one of them fixed to a tripod. The pencil-holder point of the second parallelogram extends further with an index. Also attached to the tripod holding a sheet of paper in a frame is a movable two-arm linkage with an eyepiece. To draw the perspective, one has to look at a building through the eyepiece and follow it with the index. The pencil then draws the perspective of the building automatically on the paper.

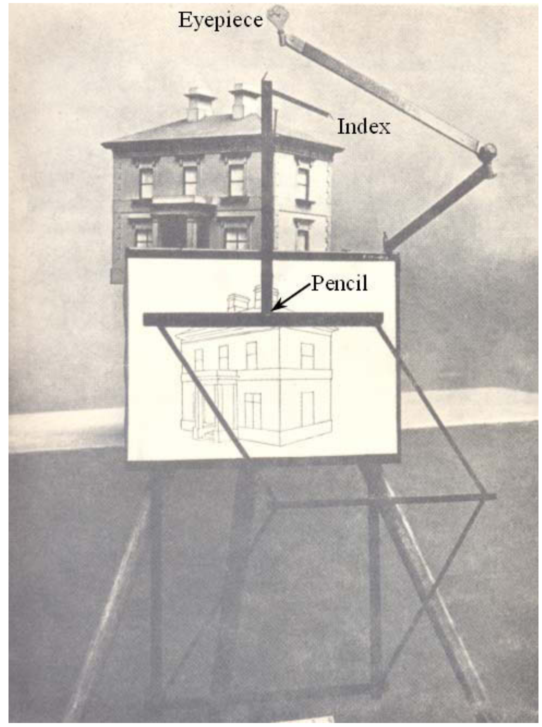

Figure 12. Watt's perspective-drawing machine [1]. He did not patent it although he had made several pieces and sold them much before he became famous.

The perspective-drawing linkage had another nice feature. The board was foldable to a reasonable size to fit in a pocket. The legs of the tripod telescoped within themselves and could be folded to form a walking stick! Watt did not patent this apparatus although he had made 50-80 pieces of this and sold them. It is reported that these still exist in different places around the world in museums and private collections.

Sculpting Linkages

Watt's inventive spirit did not age with him. When he was in his late sixties to early seventies, he started to work on sculpting machines. He did this perhaps for his amusement. In the workshop he had in his mansion 'Heathfield', where he stayed after his retirement from mainstream work, busts of Socrates and Aristotle were found. There were also two machines using which three-dimensional objects could be replicated. Published biographical accounts and Watt's letters indicate that Watt designed and built those machines himself. There were two machines: one, a proportional sculpting machine and the other, an equal-sized sculpting machine. *Figure* 13 shows the latter.

Watt's equal-sized sculpting machine used a lathe-bed (see *Figure* 13) for the base. Two tetrahedral frames were mounted on it. One frame was movable on a slide while the other was

able to rotate up and down and left and right. A number of linkages were added to balance the weight of the frames and to guide them. Also in it were a feeler to follow the contour of the original object and a tool (a variety of them specially made for him by Murdock and others) to sculpt the replica. The machine also had a treadle to power it. There was a provision to run it slowly or fast. Wood, alabaster, and other materials were used to make replicas. By simply moving the feeler over the original object and pushing the treadle, anyone could make replicas using this machine as it did not need any skill on the part of the user.

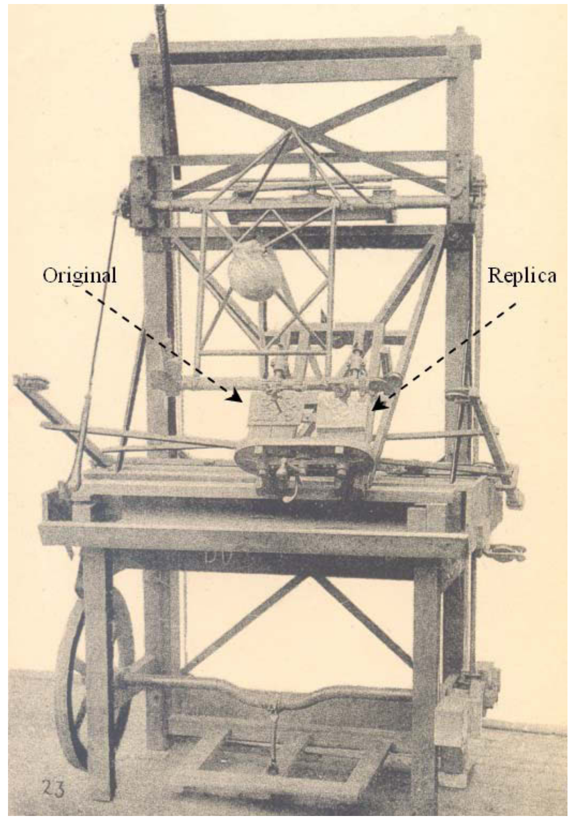

Figure 13. Watt's equal-sized sculpting machine [1]. He had also different variants of this that could make scaled replicas including miniaturized ones.

For a man who had made earlier in his life a letter-copying machine just to avoid the monotony of copying his correspondence, documents, and drawings, making a sculpting machine was probably a small modification. James Watt had many names, usually derived from Greek roots, for these machines. One such name was polyglyptic (*poly* meaning many and *glyptic* meaning carved) because his machine could do several replicas at the same time. This machine was also capable of making miniature replicas of objects. When he informed his friend about his new machine, he lamented that he could not incorporate all of his ideas into it.

Closure

H W Dickinson, who wrote a book on Watt's life and work [2], notes that Hippocrates's aphorism is apt in Watt's life: *ars longa vita brevis*, which translates to 'art is long, life is short'. James Watt died at the age of 83 in 1819 – perhaps his life was not long enough to try all his ideas for linkages.

We presented a number of linkage inventions of James Watt here but we did not mention a

number of other things he invented just to solve problems he encountered and the scientific reasoning he used in those inventions. He had observed the phenomenon of latent heat, the theory of which was propounded by his mentor and friend, Professor Joseph Black. He had guessed (some say for the first time) that water is a compound and not an element. He had improved a telemeter used to measure long distances when he worked as a civil engineer to survey canals. He had given the idea of a screw propeller to a friend. He had designed a smoke-consuming furnace. He had worked on new iron cement for sealing. He had built a mechanical counter for counting the number of strokes of the engine up to a few millions. He did not bother to patent these and a few other innovations. For him, all this was simply making the tools he needed. King Solomon (who, as the legend has it, rewarded the iron worker who made his own tools) would have surely rewarded James Watt, the super craftsman, who not only conceived and made the tools he needed but also knew much more than the tools and the craft.

Watt's life is a consummate example of a craftsman turning into an engineer and an engineer turning into a scientist. Archibald Barr, in a presidential address he gave on February 15, 1925, to the Optical Society, accurately captured Watt's personality: "*James Watt brought to bear on the practice of mechanical engineering a mind trained to consider scientifically the problems that presented themselves in his practice. He was a master in scientific reasoning based on sound knowledge of the facts and laws of the physics and chemistry of his time. His many inventions contributed more than the work of any other man towards laying the foundation for that vast and rapid development of the mechanical arts that characterized the 19th century*".

Steam engines of the kind James Watt invented are not in use today but his contributions to engineering at large remain relevant forever. When it comes to linkages, no student of kinematics misses to learn about Watt's straight-line linkage or Watt's six-bar chain. Watt's straight-line linkage is still used in some of the automobiles to prevent the undesirable movement of the axle.

Suggested Reading

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